Mem. Natl Inst. Polar Res., Spec. Issue, **48**, 216-228, 1987

PARTICLE PRECIPITATION PATTERNS IN SOUTHERN HEMISPHERE HIGH LATITUDES, LONGITUDE DEPENDENCE

J. A. GLEDHILL

Hermann Ohlthaver Institute for Aeronomy, Rhodes University, Grahamstown, 6140, South Africa

Abstract: Measurements of precipitating electron and proton fluxes in the Antarctic are reviewed. It is evident that the South Atlantic Anomaly and the large displacement of the south geomagnetic pole from the geographic pole are the dominating factors determining the distribution of particle precipitation in longitude.

Most observations of energy spectra and pitch angle distributions have been averaged over longitude and are usually given in terms of magnetic coordinates thus losing interesting data from the geographical point of view. It is suggested that it would be worth the effort to re-analyse existing data to look for spectral and pitch angle dependence on longitude in the south polar regions.

A short summary of the asymmetry between the north and south polar caps is also given.

1. Introduction

In the northern hemisphere many civilised people live north of the 50° parallel of latitude. Alaska, a large part of Canada, the United Kingdom, the whole of Scandinavia and much of Germany, Poland and the USSR lie north of 50°. Most northern hemisphere inhabitants would probably regard the term "high latitudes" as referring to those parts of the earth that lie north of the Arctic Circle, or even 70°.

In the southern hemisphere things are very different. Only one of the three land masses that project southwards reaches 50°S and even its southernmost point, Cape Horn, lies at only 56°S, a latitude comparable with those of Edinburgh, Moscow and Edmonton. Beyond that no-one lives, except the members of Antarctic expeditions, who are very temporary residents. Even islands like Gough (40°S), Marion (46°S), Kerguelen (50°S) and South Georgia (54°S) fall into the sub-Antarctic category. In this review I shall regard 50°S as the lower limit of high latitudes.

It is not only in habitation and accessibility that the two hemispheres differ so greatly. PIGGOTT (1977), has pointed out the much greater displacement of the magnetic dip pole in the southern hemisphere as compared with the more complex, double pole in the northern hemisphere. The corresponding displacement of the geomagnetic pole has two important consequences:

1) The southern auroral oval traverses a large range of geographic latitude, with a resulting pronounced effect on the distribution of particle precipitation in longitude.

2) The minimum value of the total magnetic intensity occurs in the South Atlantic Anomaly.

Both of these give rise to longitude effects on particle precipitation.

2. High Energy Particle Precipitation

Figure 1 shows the polar part of the distribution of precipitation of electrons of energy about 100 keV, observed by SEWARD in 1961 (SEWARD *et al.*, 1973) at heights of 240–410 km. (The figure is based on the corresponding part of Fig. 3 of the review by PAULIKAS (1975).) Although the central region of electron precipitation in the Anomaly lies outside our present zone of interest it is clear from Fig. 1 that its influence reaches as far south as 70°, where it impinges on the auroral zone. The figure clearly shows the longitudinal changes that would be experienced if one were to travel, for example, along the 60°S latitude line. Moving eastwards from the Greenwich meridian, the northern edge of the auroral zone is encountered at about 30°E, while the poleward edge of the zone approaches closely to the 60°S line at 120°E. Emerging from the auroral zone again at about 210°E, the line enters the westward edge of the lightly shaded region, entering the Anomaly again at about 250°E and remaining in it back to 0°.

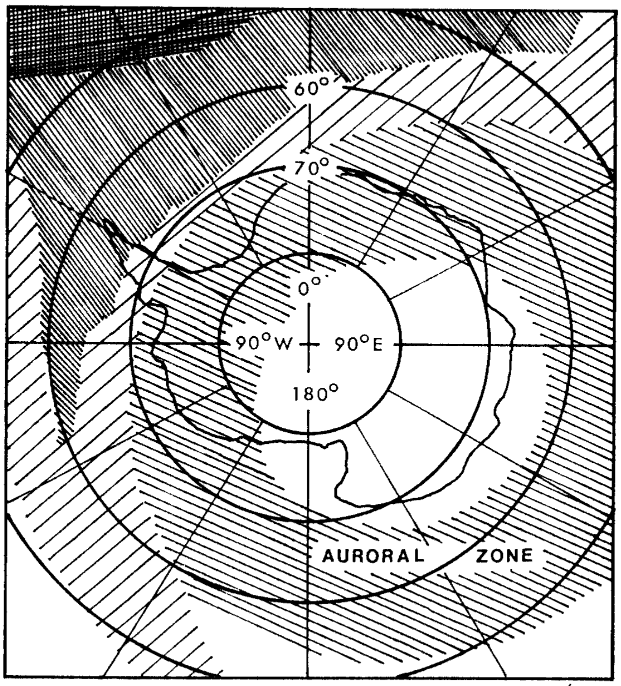

Fig. 1. Precipitation zones of electrons of energy about 100 keV observed by SEWARD in 1961 (redrawn from PAULIKAS, 1975). The two more heavily shaded regions represent the southern part of the South Atlantic Anomaly.

VOSS and SMITH (1980) have reviewed energetic particle precipitation on a global basis. In Fig. 2 the data from their Fig. 1 are redrawn in a polar coordinate format. The result is very like the 100 keV map of SEWARD *et al.* (1973), but now applies to a wide spectrum of particle energies from a number of sources. In their Fig. 5 VOSS

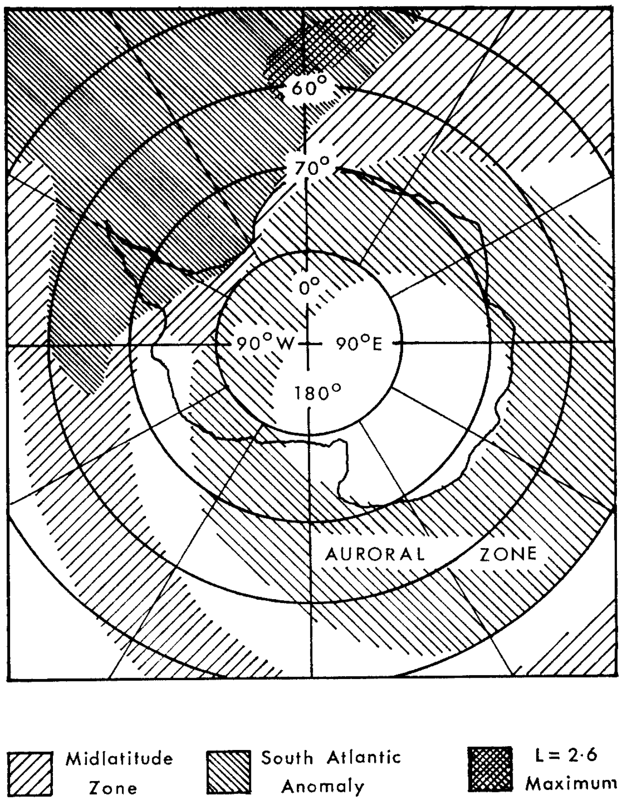

Fig. 2. South polar regions of particle precipitation from review by VOSS *and* SMITH *(1980) (redrawn from data in their Fig. 1).*

and SMITH (1980) show the nature of these particles as a function of geomagnetic latitude and the energy they carry into the atmosphere. From this it appears that the "lightly shaded region", referred to above, on SEWARD *et al.*'s map, which lies at 50°–55° geomagnetic latitude, corresponds with VOSS and SMITH's "mid-latitude zone", which has on the average about three times as much ion energy flux as electron energy flux.

It is interesting to note that this zone passes over the Antarctic Peninsula at 290°–300°E, suggesting that observing stations there should be able to note the effects of the precipitating particles in the ionosphere. HASCHICK and GLEDHILL (1974) used Alouette I measurements of the fluxes of precipitating electrons of energy in the range 40–250 keV to show that there was a good correlation between periods of precipitation and times when f_0E was abnormally high at Argentine Islands and that the observed fluxes accounted well for the increases in ionospheric ionisation.

VARGA *et al.* (1985) examined the counting rates of 1–20 keV electron detectors on the DMSP-F2 and DMSP-F3 satellites, both orbiting in nearly polar orbits at about 850 km. The counts recorded were, however, mainly due to electrons of much higher energy than 20 keV penetrating the instrument package and releasing secondaries in the spiraltron detectors.

No precise values could be given for their energies. The points in their Fig. 3b show the counting rates as the satellites crossed the L=3.5 shell in the southern hemisphere during geomagnetically quiet periods but different ring current index *Dst* (panel

A, $Dst = -5$ nT; panel B, $Dst = -15$ nT; and panel C, $Dst = -35$ nT). In all cases we note the very low counting rates between 100° and 200°E, on the opposite side of the pole to the South Atlantic Anomaly, and the maximum rates near 0°E where the L shell is closest to the centre of the southern extension of the Anomaly.

VAMPOLA and GORNEY (1983) have determined precipitating energy flux carried by electrons in the energy range 67–340 keV. Unfortunately they do not give many data in a form useful for the present paper. Their three-dimensional plot of energy flux over the South Atlantic covers only latitudes 10°N to 50°S and their plots of precipitating electron flux at L values between 6 and 9, and between 9 and 13, are in terms of magnetic local time instead of longitude. Nevertheless their Fig. 5 does illustrate the energy flux carried by electrons in the range 67–340 keV at L values between 4 and 4.25. The highest values in the southern hemisphere, of the order of 7×10^5 keV cm^{-2} s^{-1}, occur between 270° and 50°E, in the southern skirt of the South Atlantic Anomaly, as we would expect. The only energy spectrum given by these authors refers to latitudes between 17° and 50°S in the Anomaly region. Since such energy spectra are rare in our present region of interest, it is given here as Fig. 3. Note that the points are fitted remarkably well by the power law $N_e = 1.34\times10^5\ E^{-2.27}$ cm^{-2} s^{-1} sr^{-1} keV^{-1}. The S3-2 satellite from which the data were taken was well-instrumented to allow correction for penetrating particles and orbited at heights between 250 and

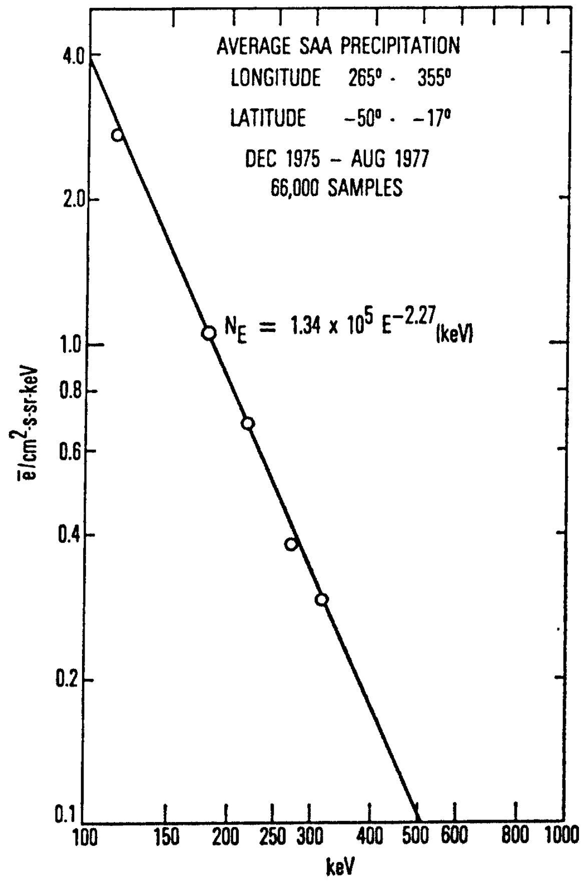

Fig. 3. Energy spectrum of the average quiet time electron precipitation in the region of the South Atlantic Anomaly (from VAMPOLA *and* GORNEY *(1983) with permission).*

1570 km. The data analysed were recorded between December 1975 and August 1977.

Further information on the high energy particles in the region is given in the paper by NAGATA *et al.* (1985), in which they report on observations of electrons in the range 0.19–3.2 MeV and protons from 0.64–35 MeV made by the satellite OHZORA between 350 and 850 km. Their Fig. 4 shows one orbit in which the satellite passes through our area of interest in the region marked D and their Fig. 5 shows the counting rates of the electron (top panel) and proton (bottom panel) detectors. Unfortunately these were saturated in the region marked D so that no values for the fluxes or spectra are available though minimum values can be deduced from the figure. The satellite was, however, spinning, and so the pitch angle distribution was recorded, as shown in Fig. 4. Recalling that in the southern hemisphere a precipitating particle has a pitch angle near to 180°, we note the depopulation of the loss cones of both protons and electrons, so that precipitating fluxes would be two or three orders of magnitude less than the trapped values.

BENBROOK *et al.* (1983) have estimated the quiet nighttime precipitating electron flux for energies above 180 keV a parachuted scintillation detector released from a Superarcas rocket at Siple, which lies in our region of interest at 76°S, 84°W. The measurements were made on 12 January 1978 at 1000 UT (0424 LT). The detector

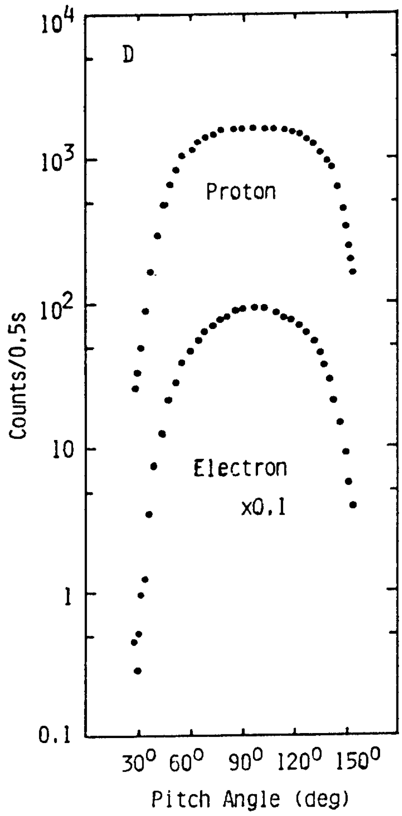

Fig. 4. Pitch angle distributions of 0.64–35 MeV protons and 0.19–3.2 MeV electrons south of −50° latitude (from NAGATA *et al. (1985) with permission).*

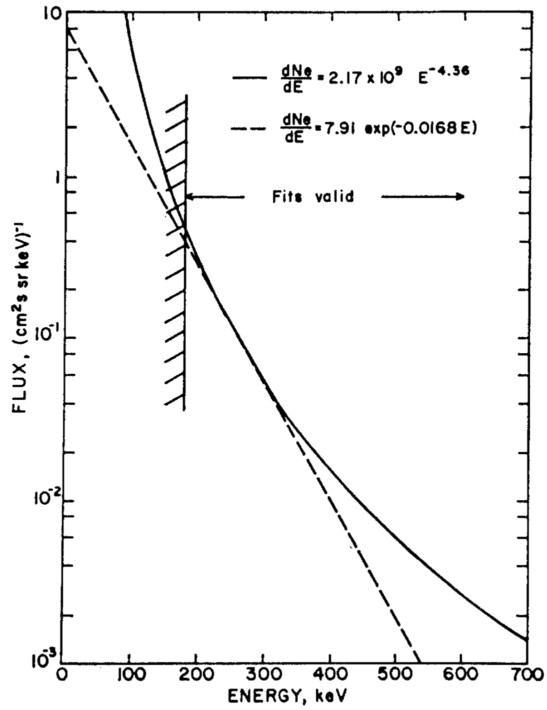

Fig. 5. Fitted electron energy spectra from X-ray measurements from a rocket at Siple (76°S, 84°W) (from BENBROOK *et al. (1983) with permission).*

counts were due to both X-ray bremsstrahlung photons and electrons and a rather complex reduction process was necessary to deduce the electron spectrum. The result is shown in Fig. 5 and the calculated ionisation rate as a function of height in Fig. 11 of the paper by BENBROOK *et al.* (1983). The spectrum is very soft but it is notable that this relatively light precipitation is the dominant source of ionisation between 65 and 95 km at night.

3. Low Energy Particle Precipitation

TORR *et al.* (1976) analysed a large data base of measurements of precipitating electrons and protons in the energy range 0.2–26 keV from the satellite Atmosphere Explorer C. The period considered was from 15 December 1973 to 25 May 1975 and the satellite was at heights of 250–300 km. Unfortunately, again, these authors did not discuss the geographical distribution of the precipitating fluxes. Their Fig. 1 illustrates the points that:

(a) the electron fluxes in the daytime were always considerably larger than the nighttime ones, especially in the invariant latitudes of the South Atlantic Anomaly; and

(b) the proton fluxes were about an order of magnitude less than those of electrons.

GLEDHILL and HOFFMAN (1981) used four years of data from the same satellite, AE-C, to determine the energy deposited by electrons in the same range, 0.2–26 keV, in the region of the South Atlantic Anomaly. They found no measurable proton fluxes and were able to use the ion channels of the particle spectrometers to correct for the high energy background. The satellite had an orbital inclination of 68° and thus gave data in the part of our region of interest that lies south of 50° latitude, almost to the 70° line. The data, however, only cover the range 270° to 30°E. This portion of their graph is redrawn in polar coordinates in Fig. 6. It differs considerably from the high energy precipitation patterns shown earlier. The dark patch about 60°–70°S, 20°–30°E, is the edge of the auroral zone and the region with precipitated energy between 2 and 3×10^{-3} μW m^{-2}, centred on 65°S, 330°E is clearly related to the Anomaly, though it is separated from the main region by a narrow minimum and an area round 50°S, 310°E where there is less than 1×10^{-3} μW m^{-2} precipitated on average. This region includes the ionosonde stations at Port Stanley and South Georgia, where particle effects are indeed much rarer than in the Antarctic Peninsula or at Halley and Sanae (RODGER *et al.*, 1981).

Like VAMPOLA and GORNEY (1983) at higher energies, GLEDHILL and HOFFMAN (1981) do not give energy spectra at the high latitudes we are considering. They did show three spectra at lower latitudes, one of which is reproduced in Fig. 7. The spectrum is harder in this energy range than in the higher range examined by VAMPOLA and GORNEY, the spectral index being approximately 1. The two spectra fit well together and suggest that a pronounced softening of the spectrum occurs in the range 30–100 keV, as VAMPOLA and GORNEY point out. No pitch angle distributions are given by either VAMPOLA and GORNEY or GLEDHILL and HOFFMAN, but TORR *et al.* (1976) state that "the pitch angle distribution was isotropic for both electrons and

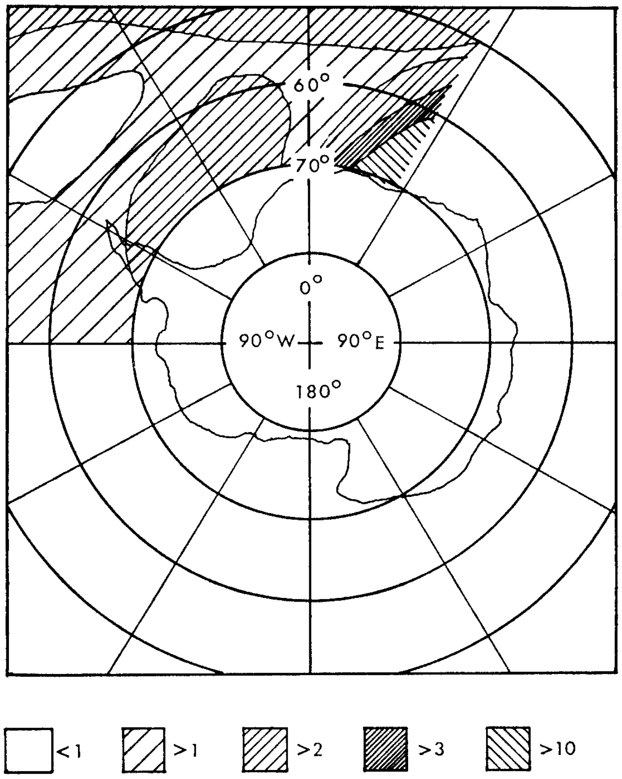

Fig. 6. Most southerly portion of quiet time precipitation pattern of 0.2–26 keV electrons. Units are $\mu W\ m^{-2}$ (redrawn from data in Fig. 8a of GLEDHILL and HOFFMAN, 1981).

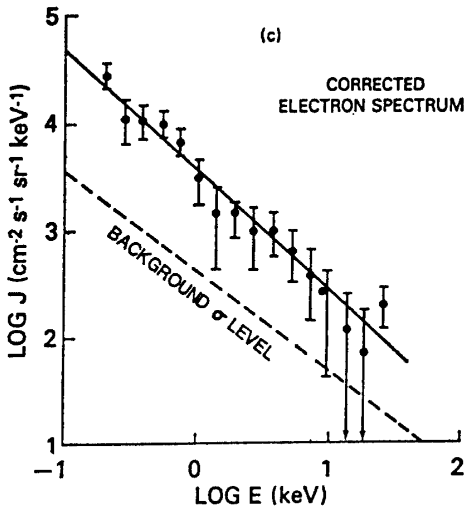

Fig. 7. Spectrum of electrons in the South Atlantic Anomaly (from GLEDHILL and HOFFMAN (1981) with permission).

protons during the daytime and nighttime" though this refers to points outside the Anomaly. All these observations refer to latitudes in the range 20°–50°S. I am not aware of any similar ones for Southern latitudes above 50°, except for the auroral zone.

Precipitation in the auroral zone is the subject of a separate paper by REES at this Workshop. I should, however, like to draw attention to the precipitation into detached arcs and patches equatorward of the aurora, studied by ANGER and his co-workers, *e.g.* WALLIS *et al.* (1979). Figure 1 of their paper shows a pass by Isis 2 over the north polar region. Comparison with auroral images from the satellite showed that the event marked with an arrow at 0718:50 coincided with the passage of the space-craft over an arc detached from the main aurora on its equatorward edge. As the spin modulation and the pitch angle distributions show, the lower energies show a filled loss cone, but a depleted conjugate loss cone and a fairly isotropic distribution outside this. The energy spectrum is shown in Fig. 8 and shows a pronounced peak at about 6 keV and a fairly rapid fall about 20 keV, especially for the precipitating electrons. Although no similar data for the southern hemisphere are presented, the authors point out that such observations have been made in the vicinity of New Zealand.

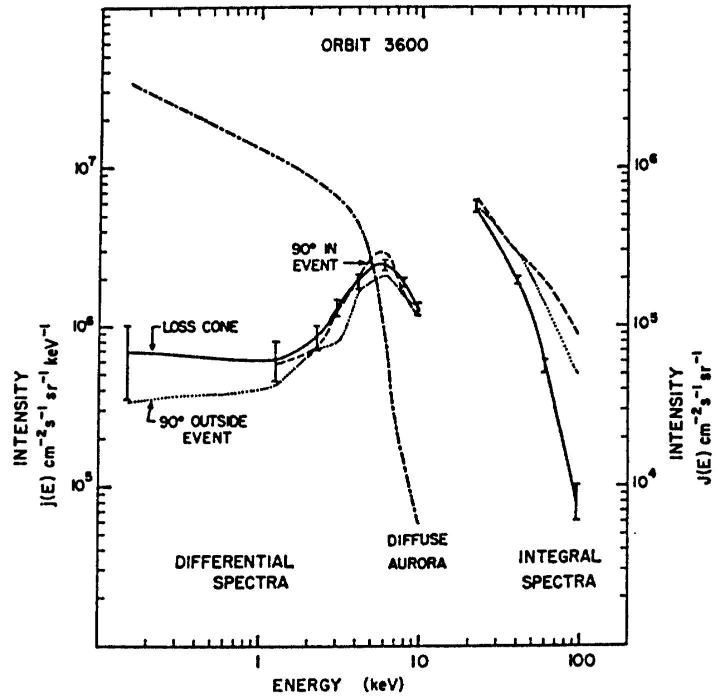

Fig. 8. Energy spectra of electrons above a detached arc next to the auroral zone, compared with that corresponding to diffuse aurora (from WALLIS *et al. (1979) with permission).*

4. Precipitation in the Polar Cap

4.1. Protons

It has been realised since the early days of satellite technology, and indeed even before, that high energy protons are precipitated into the polar caps as a reuslt of solar flares. In the late 1960's it became apparent that the fluxes in the northern and southern polar caps were usually different, and that the effects in one cap did not take place simultaneously with those in the other.

Figure 1 of the paper by EVANS and STONE (1969), illustrates the difference in intensity. We note that, whereas precipitation is fairly uniform along the satellite track in the south polar cap, the north polar trace shows a pronounced minimum at the highest invariant latitudes. Their Fig. 2 shows that the maximum values in the northern cap were much the same, and varied in much the same way, as the uniform south polar fluxes. For the first 24 h the north polar minimum remained, but eventually disappeared, after which the fluxes in the two caps were very similar. In the example given in Fig. 7 of the paper by VAN ALLEN *et al.* (1971), the situation is reversed, the south polar cap showing the minimum and the north polar cap having uniform precipitation. These authors explained the asymmetry, both in access time and in flux, in terms of the direction of the interplanetary magnetic field and anisotropy of the particle velocity distribution in the solar wind, as shown in their Fig. 10. The solar wind and interplanetary magnetic field data were obtained from Explorers 33 and 35, and the polar cap precipitation data from Injun 5, in low polar orbit. MIZERA *et al.* (1972) extended measurements down to 12 keV. Figure 9 shows one of their spectra, recorded over the south polar cap, which is well-represented by a power law with a spectral index of 1.9.

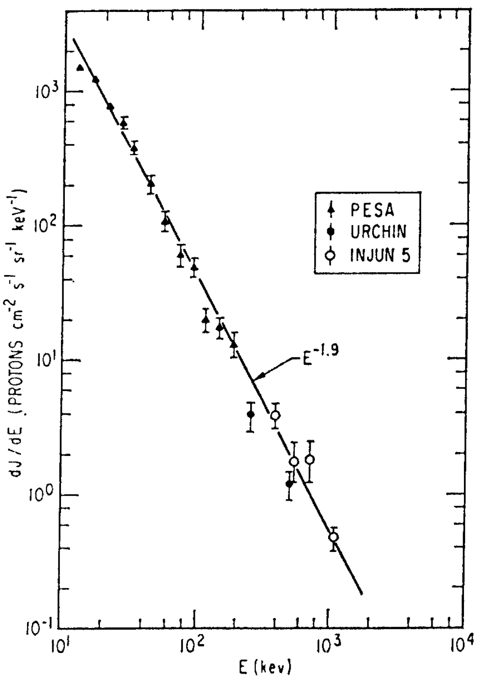

Fig. 9. Solar proton spectrum over the south polar cap (from MIZERA et al. (1972) with permission).

4.2. *Electrons*

HEIKKILA (1972) first discussed the discovery of weak, uniform electron precipitation over the polar caps, called the "polar rain". MIZERA and FENNELL (1978) reviewed satellite observations of polar precipitating electrons to that date. Figure 3 of their paper shows that, over both polar caps, the spectra are very soft and correspond remarkably well with those observed in the solar wind and the high latitude magnetospheric tail. Their Fig. 6 shows that the intensity of precipitation in the northern polar cap usually exceeds that in the southern one when the interplanetary magnetic field is directed away from the sun, whereas the flux is greater in the southern cap when the IMF is toward the sun. These observations indicate the dependence of polar cap precipitation on the IMF sector structure and support the open magnetospheric model that is now generally accepted.

GUSSENHOVEN *et al.* (1984) illustrate a commonly observed gradient of precipitation in their Fig. 1, the flux increasing from dusk to dawn in this instance. The portion of this figure on page 9789 shows an occasion when a PCA event was in progress, as is evidenced by the large average energy and total energy fluxes over the southern cap. The corresponding spectra are shown in their Fig. 2.

The characteristics of the polar rain have recently been examined by RIEHL and HARDY (1986). They found that in most cases the spectra of the polar rain could be well represented by a simple Maxwellian distribution with temperature about 80 eV and average density of the order of 5×10^{-2} cm^{-3}. Sometimes a high-energy component was also present, with temperature of the order of 500 eV and density averaging 6×10^{-4} cm^{-3}. They confirmed the very strong sector dependence mentioned above but found it impossible to distinguish the effects of the B_x and B_y components of the interplanetary field.

5. Power Line Harmonic Induced Precipitation

It has been known for some time that power line harmonics, radiated from heavy-current lines in industrial areas, penetrate into the magnetosphere, where they interact with trapped electrons and are amplified considerably (HELLIWELL *et al.*, 1975). In the process of interaction, the electron pitch angles are altered and can be scattered into the loss cone, thus inducing precipitation.

PARK and HELLIWELL (1978) have summarised the magnetospheric effects of the power line radiation. They found that radio emissions were triggered by a band of frequencies about 3 kHz, and that the interaction was with electrons in the range 0.5–10 keV energy parallel to the magnetic field. The emissions were particularly intense in the quiet period following a magnetic storm, as would be expected on account of the increased electron population during such times.

LUETTE *et al.* (1977) have examined the longitudinal variation of the VLF chorus activity. Figure 3 of their paper shows that the percentage occurrence is in fact greater on the average in the southern hemisphere, particularly in the region between 60° and 72° invariant latitude.

TATNALL *et al.* (1983) have discussed the world-wide distribution of VLF-emissions observed with the satellites Ariel 3 and 4. In their Fig. 10 they show a map, comparing the regions of most intense emission with the distribution of towns of more than 100000 population. The coincidence of the main regions with industrialised countries is obvious. Also shown are the conjugate areas in the southern hemisphere, to which these harmonics propagate in the whistler mode. Figure 2 (iv) c of their paper shows the world map in more detail, especially the southern conjugate regions. The conjugate area to North America, centred on 60°S 250°E, is one of the most striking features of the map. The contours are for the fractional occurrence (10=100%) of a power level 30 dB above 4.8×10^{-19} W m^{-2} Hz^{-1} at 3.2 kHz, when $Kp\leqslant2+$. This is in the middle of the frequency range showing the greatest degree of interaction with the trapped electron population (PARK and HELLIWELL, 1978).

The southern portion of this figure is redrawn in polar coordinates in Fig. 10. The conjugate to the North American industrial area and part of that of the European area lie in our region of interest. In particular, the most intense part of the western area is close to the US base at Siple in Antarctica. Much of the research described above was in fact carried out at Siple and at its predecessor, Eights.

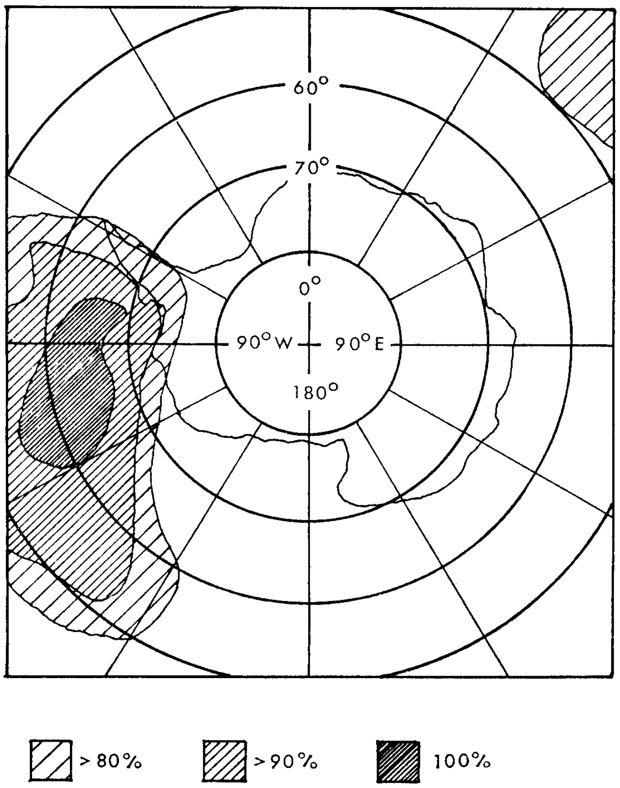

Fig. 10. Contours of fractional occurrence of a power level 30 dB above 4.8×10^{-19} W $m^{-2}Hz^{-1}$ at 3.2 kHz when $Kp \leqslant 2+$ (redrawn from data in Fig. 2 (iv) c of TATNALL et al. (1983)).

It does not appear that the precipitating electrons have been directly detected in such events. The electrons measured by BENBROOK *et al.* (1983) at Siple were precipitating during a period of low VLF activity; though it is probable that some of the flux was due to power line harmonic interaction, it is by no means certain that this was so.

INAN *et al.* (1985) have observed perturbations in the phase of VLF waves from Omega and other transmitters, as recorded at Palmer Station (65°S, 64°W). These short duration phase changes, lasting 30 s or so, coincided with lightning induced whistlers, which presumably caused pitch angle scattering and hence electron precipitation in the energy range 40–250 keV. This in turn increased the ionisation rate, and hence the electron density, in the *D* region of the ionosphere, which forms the upper conductor of the wave guide in which the VLF waves propagate. This produces a lowering of the reflection height by 1 km or so and so results in a phase advance. While this theory seems to explain the observations of these "Trimpi effects", it is very desirable that observations should be made of the precipitating electrons themselves, or even their accompanying 391.4 or 427.8 nm radiation.

6. Conclusions

It is clear that the Antarctic is a unique region from the point of view of the longitudinal distribution of particle precipitation and that much more remains to be done to elucidate its intricacies. In particular measurements of particle energy spectra and especially pitch angle distributions would help in evaluating the energy input to the upper atmosphere and the effects on the transmission of radio waves due to the ionospheric consequences of this precipitation. Ground-based, rocket, balloon and satellite data can contribute to the study of these effects.

References

BENBROOK, J. R., BERING, E. A., III, LEVERENZ, H., ROEDER, J. L. and SHELDON, W. R. (1983): Quiet-time electron precipitation at L=4 in the South Atlantic Anomaly. J. Geophys. Res., **88**, 189–199.

EVANS, L. C. and STONE, E. C. (1969): Access of solar protons into the polar cap, a persistent north-south asymmetry. J. Geophys. Res., **74**, 5127–5131.

GLEDHILL, J. A. and HOFFMAN, R. A. (1981): Nighttime observations of 0.2 to 26 keV electrons in the South Atlantic Anomaly made by Atmosphere Explorer C. J. Geophys. Res., **86**, 6739–6744.

GUSSENHOVEN, M. S., HARDY, D. A., HEINEMANN, N. and BURKHARDT, R. K. (1984): Morphology of the polar rain. J. Geophys. Res., **89**, 9785–9800.

HASCHICK, A. D. and GLEDHILL, J. A. (1974): Ionization of the E region of the ionosphere by precipitated electrons. S. Afr. J. Antarct. Res., **4**, 16–22.

HEIKKILA, W. J. (1972): Penetration of particles into the polar cap and auroral regions. Critical Problems of Magnetospheric Physics, ed. by E. R. DYER. Washington, D.C., IUCSTP Secretariat, 67–82.

HELLIWELL, R. A., KATSUFRAKIS, J. P., BELL, T. F. and RAGHURAM, R. (1975): VLF line radiation in the earth's magnetosphere and its association with power system radiation. J. Geophys. Res., **80**, 4249–4258.

INAN, U. S., CARPENTER, D. L., HELLIWELL, R. A. and KATSUFRAKIS, J. P. (1985): Subionospheric VLF/LF phase perturbations produced by lightning-whistler induced particle precipitation. J. Geophys. Res., **90**, 7457–7469.

LUETTE, J. P., PARK, C. G. and HELLIWELL, R. A. (1977): Longitudinal variations of very-low-frequency chorus activity in the magnetosphere; Evidence of excitation by electrical power transmission lines. Geophys. Res. Lett., **4**, 275–278.

MIZERA, P. F. and FENNELL, J. F. (1978): Satellite observation of polar, magnetotail lobe and interplanetary electrons at low energies. Rev. Geophys., **16**, 147–153.

MIZERA, P. F., FENNELL, J. F. and BLAKE, J. B. (1972): Polar cap measurements of solar flare protons with energies down to 12.4 keV. J. Geophys. Res., **77**, 4845–4850.

NAGATA, K., KOHNO, T., MURAKAMI, H., NAKAMOTO, A., HASEBE, N., TAKENAKA, T., KIKUCHI, J. and DOKE, T. (1985): OHZORA high energy particle observations. J. Geomagn. Geoelectr., **37**, 329–345.

PARK, C. G. and HELLIWELL, R. A. (1978): Magnetospheric effects of power line radiation. Science, **200**, 727–730.

PAULIKAS, G. A. (1975): Precipitation of particles at low and middle latitudes. Rev. Geophys., **13**, 709–734.

PIGGOTT, W. R. (1977): The importance of the Antarctic in atmospheric sciences. Philos. Trans. R. Soc. London, Ser. B, **279**, 275–285.

RIEHL, K. B. and HARDY, D. A. (1986): Average characteristics of the polar rain and their relationship to the solar wind and the interplanetary magnetic field. J. Geophys. Res., **91**, 1557–1571.

RODGER, A. S., FITZGERALD, P. H. and BROOM, S. N. (1981): The nocturnal intermediate layer over South Georgia. J. Atmos. Terr. Phys., **43**, 1043–1050.

SEWARD, F. D., GRADER, R. J., TOOR, A., BUNGINYUN, G. A. and HILL, R. W. (1973): Electrons at low altitudes; A difficult background problem for soft X-ray astronomy. Rep. UCRL–51470, Livermore, Univ. of Calif. Lawrence Livermore Lab.

TATNALL, A. R. L., MATTHEWS, J. P., BULLOUGH, K. and KAISER, T. R. (1983): Power line harmonic radiation and the electron slot. Space Sci. Rev., **35**, 139–173.

TORR, D. G., TORR, M. R., HOFFMAN, R. A. and WALKER, J. C. G. (1976): Global characteristics of 0.2 to 26 keV charged particles at F region altitudes. Geophys. Res. Lett., **3**, 305–308.

VAMPOLA, A. L. and GORNEY, D. J. (1983): Electron energy deposition in the middle atmosphere. J. Geophys. Res., **88**, 6267–6274.

VAN ALLEN, J. A., FENNELL, J. F. and NESS, N. F. (1971): Asymmetric access of energetic solar protons to the earth's north and south polar caps. J. Geophys. Res., **76**, 4262–4275.

VARGA, L., VENKATESAN, D. and MENG, C.-I. (1985): Low altitude observations of the energetic electrons in the outer radiation belt during isolated substorms. Planet. Space Sci., **33**, 1259–1266.

VOSS, H. D. and SMITH, L. G. (1980): Global zones of energetic particle precipitation. J. Atmos. Terr. Phys., **42**, 227–239.

WALLIS, D. D., BURROWS, J. R., MOSHUPI, M. C., ANGER, C. D. and MURPHREE, J. S. (1979): Observations of particles precipitating into detached arcs and patches equatorward of the auroral oval. J. Geophys. Res., **84**, 1347–1360.

(Received November 4, 1986; Revised manuscript received March 4, 1987)